SIMULATION STUDY ON INFLUENCE OF LEAFLET SHAPE AND OPEN ANGLE OF TRI-LEAFLET MECHANICAL HEART VALVE ON BLOOD FLOW

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Abstract

A mechanical heart valves is a device implanted in patients with the dysfunctional heart valves. It has been using to save many lives. Several types of mechanical heart valves have been developed to improve hemodynamic of blood that flows through the valves. The open angle and the curvature of leaflet of the mechanical heart valves may affect the hemodynamic of blood flow. Therefore, this paper was aimed to study on the influence of fully open angle and the curvature of the leaflet shape of the valves on velocity and shear stress of blood flow through tri-leaflet mechanical heart valves. This paper studied on three dimensional models of eight tri-leaflet mechanical heart valves: flat tri-leaflet heart valves at the fully open angles of 85, 87, and 90 degree, curved tri-leaflet heart valves with the curved inner radius of 8.672 mm at fully open angle of 85, 87, and 90 degree, curved tri-leaflet heart valves with the curved inner radius of 8 and 9.328 mm at fully open angles of 85 degree. The SST k-ω turbulent model in FLUENT was applied to analyse unsteady incompressible blood flow. As the results of computational simulation, the maximum shear stress was found at after peak systole phase in both flat and curved tri-leaflet heart valves. The flat tri-leaflet heart valve at the fully open angle of 90 degree provided the highest shear stress of blood flow compared with the flat tri-leaflet heart valves at other levels of open angle. While the curved tri-leaflet heart valve at the fully open angle of 85 degree provided the highest shear stress of blood flow compare with the curved tri-leaflet heart valves at the other levels of open angle. The highest velocity was found in the region between leaflets for all types of tri-leaflet heart valves, resulting in high shear stress in that region. Therefore, the fully open angle and the leaflet shape of tri-leaflet heart valves affect to velocity profile and shear stress of blood flow that may lead to blood clotting conditions in the mechanical heart valves.

Keywords: **Tri-leaflet mechanical heart valves; leaflet shape; leaflet open angle**

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Introduction

The human heart is an important organ of the human body. It pumps and circulates throughout the body via the circulatory system. It consists of four chambers: upper left atrium, upper right atrium, lower left ventricles, and lower right ventricles. Each heart chamber has different roles. Oxygen-poor blood returned from the vein enters into the right atria. When the right atrium contracts, blood is pumped into the right ventricle. After that blood is pumped through the pulmonary circulation via pulmonary arteries to purify blood in the lung. The left atrium receives oxygenated blood from the lung via the pulmonary vein. Then, oxygenated blood is pumped into the left ventricle that pumps blood into the aorta to disperse blood throughout the systemic circulation. At the connections between the heart chambers, there are heart valves to prevent backflow of blood to the anterior chambers. The heart chambers are separated by four valves: the tricuspid, pulmonary, mitral, and aortic valves.

When one of native heart valves does not work properly, it can be one cause of heart valve diseases. Rheumatic fever, degeneration related age changes, and infection cause the changes in the flexibility and shape of a native heart valves. A dysfunctional heart valves increase workload for the heart to supply blood through the circulatory system. Patients with dysfunctional heart valves who receive delayed and discontinued treatment may confront with the heart failure, atrial fibrillation, endocarditis, pulmonary hypertension, and blood clots. The remedy of heart valves diseases can be treated by taking medicines, repairing or replacing the heart valves. The treatment depends on the doctor diagnoses that consider based on many factors, including severity of heart valve disease, and the age of patients. Patients who have severe symptoms, need to be treated by replacing heart valves with prosthesis heart valves.

Prosthesis heart valves have been using for valves replacement for decades. There are two major types of the prosthesis heart valve: biological prosthesis heart valves and mechanical heart valves. The biological prosthesis heart valves are tissue heart valves that have risk of valve deterioration. Elderly patients are more suitable to implanted with biological prosthesis because this type of the valve has low lifespan.

Another type of prosthesis heart valves are mechanical heart valves (MHVs) that are medical devices, for patients who need long lifetime of the valve. They are durable to implant with mechanical heart valves. Several types of mechanical heart valves (MHVs) have been developing, e.g. caged ball valves, mono-leaflet, bi-leaflet, and tri-leaflet valves (Pibarot *et al.*, 2009). A caged ball valve is the first type of mechanical heart valve that has a blood flow channel around a ball. It induces a high risk of blood clots formation. Currently it has discontinued to be produced commercially. A mono-leaflet MHV was designed to develop a flow channel around a single leaflet that has two different sizes of orifice, leading to a difference in velocity blood flow through two orifices. This difference causes stagnation flow, leading to thrombosis. A bi-leaflet MHVs was developed from the mono-leaflet. This device has a flow channel with two leaflets, It makes smaller regions of flow separation from the orifice and lower reverse flow of the valves (Yoganathan *et al.*, 2004). Although the mono-leaflet MHV has a lower risk of thrombosis compared with caged ball valves, a study of Lee *et al.* (2006) investigated a valve closing velocity of mono-leaflet and bi-leaflet by charge-coupled device. Their results showed that a bi-leaflet had lower closing velocity compared with the mono-leaflet. A valve closing velocity affected a cavitation bubbles generation that might cause a blood cell damage. A tri-leaflet MHV is a MHV that was developed to imitate native heart valve, blood flows along central channel of the valve is similar to the flow through the biological prosthesis. Although, MHVs have a long life span, patients with MHVs may confront with after surgery obstacles, including hemolysis that damages red blood cells and platelet destruction. The destruction of red blood cell and platelet can induce thrombus formation around the leaflet and housing of MHVs prostheses (Hong and Kim, 2011). Several recent studies have suggested that the hemodynamics of blood flow through the MHVs plays dominant role in the thrombus formation (Cheng *et al.*, 2004; Krishnan *et al.* 2006). Types of MHVs influence jet flow, shear stresses elevation, flow separation and recirculation, shed vortices, and turbulence of blood flow. That factor may induce platelet activation and lead to the formation of blood clots. Thus, MHVs have been designing based on hemodynamic improvement to minimize the thrombus deposition. Grigioni *et al.* (2001) tested a turbulent shear stress of a two bileaflet valves using Laser Doppler anemomentry, although they are very similar in design. the concept of curved wake could conclude that the curvature of the leaflets' surface must be identified as an important parameter. Li *et al.*, (2011) compared shear stress between bi-leaflet and trileaflet MHVs via Mock Circulatory Loop System. The magnitudes of the shear stresses of blood flow in both tri-leaflet heart valve and bi-leaflet heart valve are similar. The tri-leaflet MHVs imitated from actual tri-leaflet tissue heart valves are promising to use and perform on comparable safety levels to bi-leaflet mechanical heart valves (Gallegos *et al.*, 2006; Kiang-ia and Chatpun, 2013). This study is aimed to study the influence of curvature and fully open angle of a tri-leaflet mechanical heart valves on shear stress and velocity of blood flow through the valves. The design parameter of shear stress and velocity blood flow of tri-leaflet MHVs primarily investigates a factor of blood flow through leaflet valves for results to expected to using in modification of leaflet shape and fully open angles of tri-leaflet mechanical heart valves design.

Materials and Methods

In this paper, the models of MHVs had a diameter of 27 mm for all models. The curved leaflet were designed with leaflet width (w) at 16 mm, the radius of the leaflet curve (R) were 0.5 w, 0.542 w, and 0.583 w. The schematic dimension is shown in Figure 1. The fully open angles were designed with 85, 87, and 90 degree as in Figure 2.

The leaflet valves were simulated to locate at aortic position. The 3D models of MHVs were created using SOLIDWORK. A tri-leaflet MHVs models was designed with different leaflet shape and fully open angles as shown in Table. 1. The flat tri-leaflet MHVs were designed with a three models with fully open angles of 85, 87, and 90 degree. The curved tri-leaflet MHVs were designed with three different inner radi of 8, 8.672, and 9.328 mm at the open angles of 85, 87, and 90 degree, respectively.

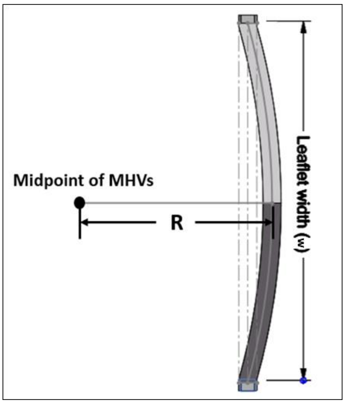

Figure 1. A leaflet shapes MHVs design

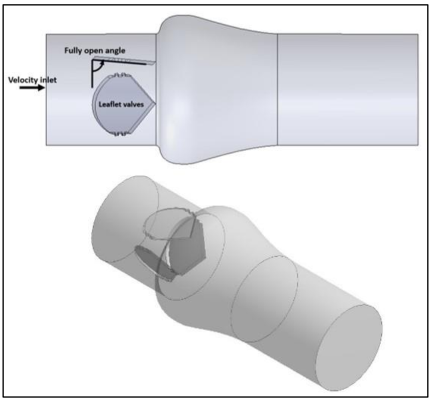

Figure 2. geometrical aortic position with leaflet valves model

Table. 1. Tri-leaflet MHVs models type

Models of tri-leaflet MHVs	Curved inner radius (mm)	Fully open angle (degree)
Flat tri-leaflet MHVs Model 1	-	85
Flat tri-leaflet MHVs Model 2	-	87
Flat tri-leaflet MHVs Model 3	-	90
Curved tri-leaflet MHVs Model 4	8.672	85
Curved tri-leaflet MHVs Model 5	8.672	87
Curved tri-leaflet MHVs Model 6	8.672	90
Curved tri-leaflet MHVs Model 7	9.328	85
Curved tri-leaflet MHVs Model 8	8	85

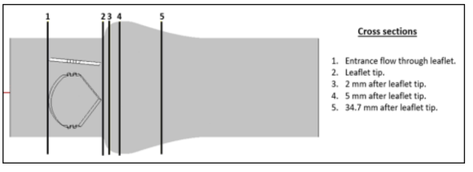

Figure 3. The cross sections of MHVs models for mechanical heart valves

The computational simulation was based on the finite volume method using ANSYS fluent. Boundary conditions were set based on Shahriari *et al.* (2012). The inlet pulsatile velocity flow inlet was applied at the left ventricle side of the model as in Figure 2. The blood flow was modeled as unsteady incompressible turbulent flow using SST k-omega turbulent model. The blood properties were considered to be constant along the flow channel, density of blood is 1056 kg/m^3, and dynamic viscosity is 3.5×10^{-3} Pa.s (Shahriari *et al.*, 2012).

This paper analyzed shear stress and velocity profiles with five cross sections as shown in Figure 3: flow entrance, leaflet tip, 2 mm after leaflet tip, 5 mm after leaflet tip, and 34.7 mm after leaflet tip section. Shear stress and velocity profiles of blood flow were considered in each cross sections.

For the effect of leaflet shaped of MHVs, the shear stress and velocity of blood flow were investigated in different models of MHVs: model 1, model 4, model 7, and model 8. While effect of the leaflet shape and fully open angle analyzed the shear stress and velocity of blood flow were analyzed in the model 1, model 2, model 3, model 4, model 5, and model 6.

Theories and Principles

The physical phenomena of blood flow is governed by the conservation of mass and the conservation of momentum. The blood flow was considered to be incompressible turbulent flow. Mathematical model of the blood flow governed by the Reynolds-averaged Navier-Stokes (RANS) equations is given in Equation (1)

$$\frac{\partial\left(\rho u_i u_j\right)}{\partial x_i} = -\frac{\partial P}{\partial x_i} + \frac{\partial}{\partial x_i}\left(\mu\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right)\right) + \frac{\partial}{\partial x_i}\left(-\rho\overline{u_i' u_j'}\right) \quad (1)$$

where ρ is flow density, u is flow velocity, P is pressure, and μ is dynamic viscosity. i, j are the unit vectors in the horizontal and radius directions, respectively.

The effect of turbulent fluctuations, $-\rho\overline{u_i' u_j'}$ is called the reynolds stresses. The Reynolds stresses relates to the mean velocity gradients based on Boussinesq hypothesis as in Equation (2):

$$-\rho\overline{u_i' u_j'} = \mu\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right) - \frac{2}{3}\left(\rho k + \mu_t \frac{\partial u_k}{\partial x_k}\right)\delta_{ij} \quad (2)$$

where k is turbulent dissipation rate. The SST k-omega model was selected as the turbulent model in the study.

Results and Discussion

To validate a results of the numerical study were set base on boundary condition with

Bluestein *et al*. (1999). The velocity profile of blood flow through the bi-leaflet MHVs obtained from 2D and 3D numerical simulations were compared with the velocity profile of blood flow at the leaflet tip obtained from the study of Bluestein *et al*. (1999). The numerical results are in good agreement with the results of Bluestein *et al*. (1999) as in Figure 4.

Figure 5 shows the variation of shear stress and velocity along the diameter of the flat tri-leaflet MHVs at fully open angle of 85 degree in a cross section 1 at the time of 105, 300, 600, and 800 ms. The shear stress of blood flow through the flat tri-leaflet MHVs varied with time. The highest shear stress was appears at 105 ms after peak systole phase, it was found nearly aortic sinus. This phase had the highest shear stress. The high shear stress causes a high risk of blood cells damage, leading to hemolysis and platelet activation.

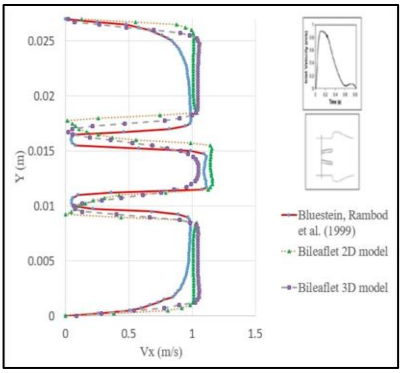

Figure 4. Comparison of velocity profile at the leading edge (at 105 ms after Peak Systole) obtained from the study of Bluestein *et al*. (1999), 2D and 3D simulation results of the flow through bi-leaflet valve

Effect of Leaflet Shape on Shear Stress and Velocity Profile of Blood Flow Through Tri-Leaflet Mechanical Heart Valves

As the results of shear stress and velocity at each time step, the shear stress and velocity varied with the time and velocity inlet. In this section, the highest level of shear stress and velocity at 105 ms after peak systole phase was considered. At the cross section 2, high shear stress and velocity profiles were found near the leaflet tip that may cause high risk of blood clots in MHVs. The leaflet shapes were modeled at the same fully open angle 85 degree to investigated shear stress and velocity profiles in: model 1, model 4, model 7, and model 8 as shown in Figure 6. The maximum shear stress obtained from the model 4, model 7, model 8, and model 1 were 9.81 Pa, 9.07 Pa, 5.08 Pa, and 4.29 Pa, respectively. The maximum shear stress obtained from the

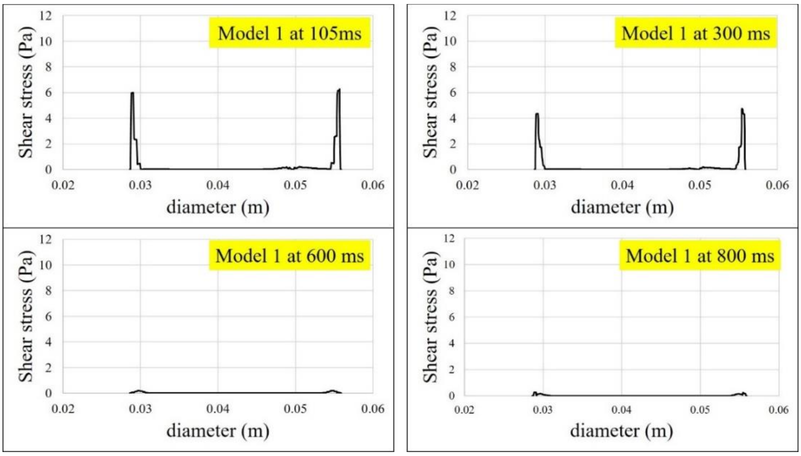

Figure 5. Comparison a shear stress and velocity profiles in the flat tri-leaflet mechanical heart valve with open angle 85 degree with a 105, 300, 600, and 800 ms

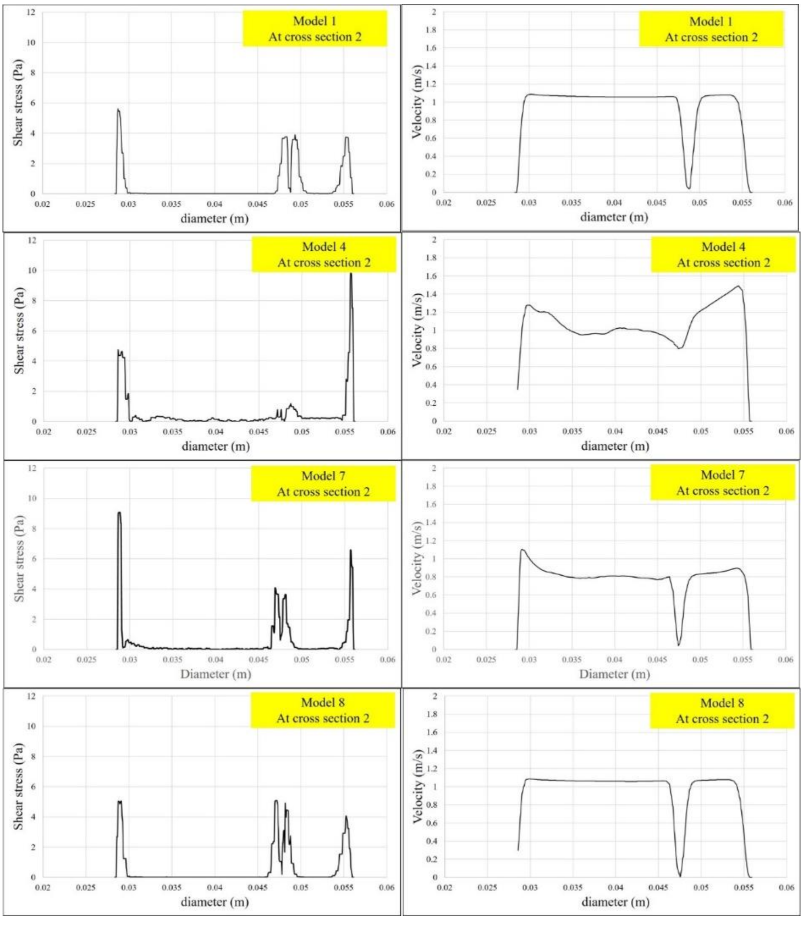

Figure 6. Comparison a shear stress and velocity profiles of tri-leaflet mechanical heart valves (model 1, model 4, model 7, and model 8)

model 4 and model 7 were found at nearly aortic sinus, however low shear stress was found at between leaflets area. On the other hand, in the model 1 and model 8, low shear stress located at aortic sinus area while a the maximum shear stress locate between leaflets. As the results of velocity profiles, in the model 1 and model 8, the maximum velocity gradient observed nearly between leaflets, resulting in high shear stress. In the model 4 and model 7, low velocity gradient appeared nearly between leaflets. Whereas a velocity gradient occurred along cross section in the model 1 and model 8. High velocity gradient causes high shear stress that may induce more blood cell damage along cross section in the model 1 and model 8. The different leaflet shape resulted in the difference in shear stress and velocity profile of blood flow through a tri-leaflet MHVs that can induces a platelet activation and blood cell damage occurs in a different area in tri-leaflet MHVs.

Effect of Fully Open Angles on Shear Stress and Velocity Profile of Blood Flow Through a Flat Tri-Leaflet Mechanical Heart Valves

In this section, shear stress and velocity profiles of blood flow through flat tri-leaflets at fully open angle 85, 87, and 90 degree (model 1, model 2, model 3, model 4, model 5,

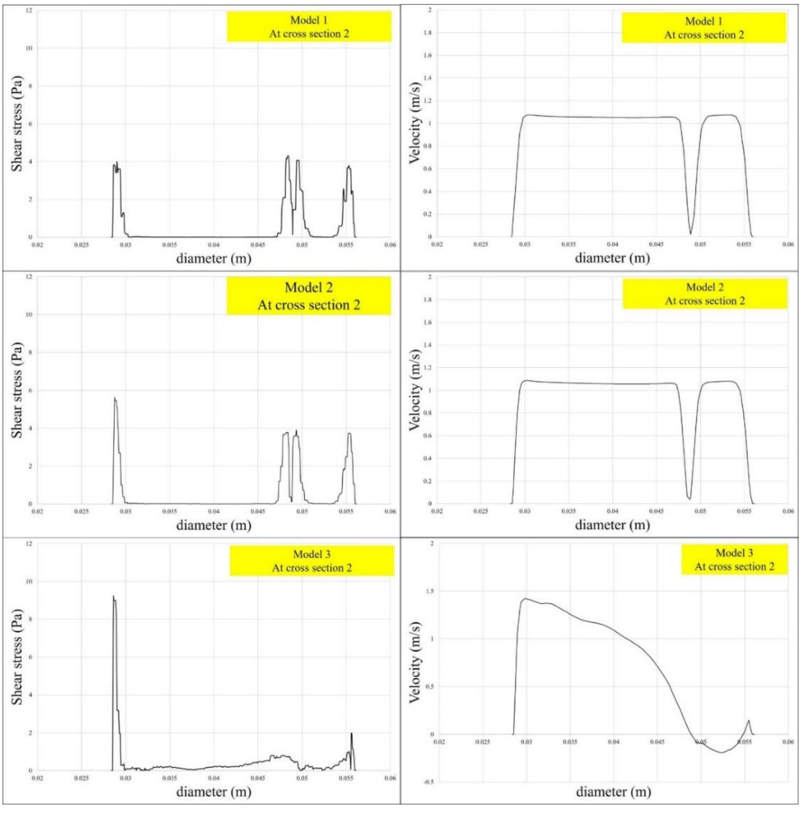

Figure 7. Comparison a shear stress and velocity profiles of tri-leaflet mechanical heart valves (model 1, model 2, and model 3)

and model 6) were investigated to studies the effect of fully open angles on shear stress and velocity profiles of blood flow. Figure 7 shows shear stress and velocity profiles of blood flow through flat tri-leaflet MHVs model 1, model 2, and model 3. The results show that the maximum shear stress in model 3, model 2, and model 1 were 9.24 Pa, 5.63 Pa, and 4.29 Pa, respectively. Different fully open angles provided different shear stress and velocity profiles. Model 2 and model 3 that had larger fully open angle compared with the model 1 caused has change velocity gradient in the aortic sinus, generating higher shear stress at nearly aortic sinus than that in the model 1. However low velocity gradient has between leaflet area, generating low shear stress between leaflet region. In the model 3 the maximum shear stress appeared at the aortic sinus area, resulting in high shear stress along cross section. While velocity profiles of blood flow in the model 3 show the back flow of blood between leaflets.

Effect of Open Angles on Shear Stress and Velocity Profile of Blood Flow Through a Curvature Tri-Leaflet Mechanical Heart Valves

Figure. 8 shows the shear stress and velocity profiles of blood that flowed through curved tri-leaflet MHVs with fully open angle of 85, 87, and 90 degree. The results show that the maximum shear stress of blood flow obtained from the model 4, model 5, and model 6 were 9.81 Pa, 8.98 Pa, and 3.99 Pa, respectively. The increasing of fully open angle caused the change a velocity profiles with lower velocity gradients at aortic sinus

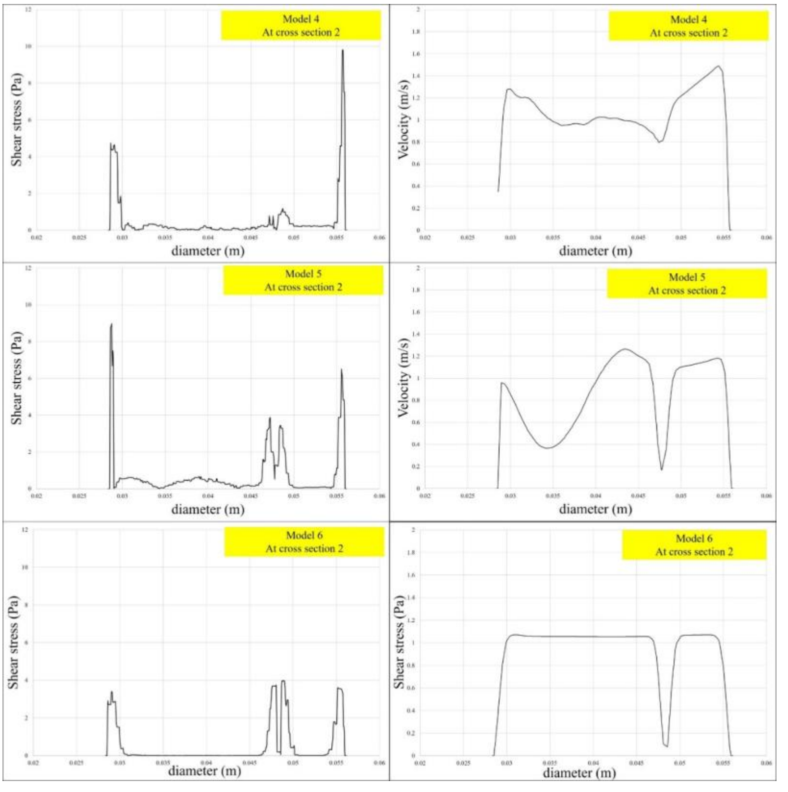

Figure 8. Comparison a shear stress and velocity profiles of tri-leaflet mechanical heart valves (model 4, model 5, and model 6)

area and higher velocity gradient at between leaflet area. The high shear stress was generated in different areas of curved tri-leaflet models based on velocity gradient.

The high shear stress found at aortic sinus has increase a higher risk of blood clotting potential due to aortic sinus area has a large recirculation to allow platelet to a trap (Bang *et al.*, 2006). For an estimation, the shear stress must above 150 Pa to cause blood damage and above 10 Pa to cause platelet activation (Ge *et al*., 2008). Although, shear stress in this study was below 10 Pa of all tri-leaflet MHVs models that platelet activation initiation but blood clotting can occur from many factors such as cavitation, stagnation flow, pressure drop and recirculation region. In this study, blood clotting can be considered from recirculation region factor. Figure. 9 shows the comparison of streamline of blood flow between tri-leaflet mechanical heart valves with flat tri-leaflet and curved tri-leaflet at after peak systole phase (105 ms), resulting a recirculation flow in flat-trileaflet model 1 and model 2 (fully open angle: 85 and 87 degree) has occur at aortic sinus regions, model 2 has a larger recirculation flow region than a model 1.

A recirculation flow region in model 3 was larger compared with model 1 and model 2, nearly leaflet tip. Model 4 and model 5 has a different position and magnitude of recirculation flow, a recirculation flow region has large and occurs at nearly aortic sinus position. Model4 and model 5 provided larger recirculation region than model 6. A recirculation flow has a important factor allows a platelet to be a trapped (Yun BM *et al*., 2014). The model 3 had a larger a recirculation that caused a larger area of

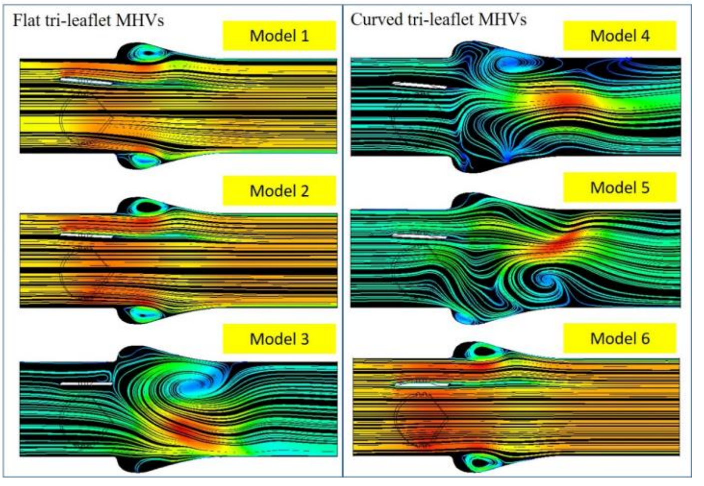

Figure 9. Comparison a streamline of tri-leaflet mechanical heart valves

platelet trap region than model 1 and model 2. Thus, the model 3 had a higher shear stress than model 1 and model 2. Model 3 has a highest risk of blood clotting in flat tri-leaflet mechanical heart valves model with high risk of platelet activation and larger platelet to be a trapped region wherewith a position of recirculation flow region and maximum shear stress occurs at nearly a recirculation area. Although, a model 1 had similar recirculation region compared with model 2 but model 1 has the lowest shear stress amongs flat tri-leaflet heart valve models that cause the lowest risk of blood clotting compared with flat tri-leaflet models. From curved tri-leaflet mechanical heart valve models, the model 6 had similar recirculation flow region occured in the model 1 and the model 2, resulting in the lowest shear stress in curved mechanical heart valve models and leading to the lowest risk of blood clotting in curved mechanical heart valves models. Although, model 4 and model 5 had a higher risk of platelet activation but a platelet trap region occurs in different area. In the model 4, the trap region occurs at nearly leaflet tip, leading to blood clot in leaflet.

These study compared effect of leaflet shape and fully open angle can cause change areas of shear stress and velocity profiles that found a risk of blood cell damage, higher risk of platelet activation lead to blood clotting at a difference areas.

Conclusions

The shear stress and velocity in MHVs were investigated numerically in tri-leaflet MHVs with different with open angle and leaflet shape. As the results of the study. The flat tri-leaflet MHVs with open angle 85 degree provided the lower shear stress on blood flow that caused the lowest risk of blood clotting than the other level of open angle with same types. On the other hand, the curved tri-leaflet MHVs with open angle 90 degree provided the different results compared with the flat tri-leaflet MHVs. The leaflet shape and open angle affect the shear stress and velocity of blood flow, these factors should be appropriately considered when designed MHVs to reduce high risk of blood clotting and platelet activation from shear stress.

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